Accident Analysis and Prevention 119 (2018) 195–201

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Heat waves and fatal traffic crashes in the continental United States

Connor Y.H. Wu[a,*], Benjamin F. Zaitchik[b], Julia M. Gohlke[c]

[a] Department of Social Sciences, College of Arts and Sciences, Troy University, Troy, AL, 36082, USA
[b] Department of Earth and Planetary Sciences, Zanvyl Krieger School of Arts & Sciences, Johns Hopkins University, Baltimore, MD, 21218, USA
[c] Department of Population Health Sciences, Virginia-Maryland College of Veterinary Medicine, Virginia Tech, Blacksburg, VA, 24061, USA

ARTICLE INFO

Keywords:
Climate change
Heat waves
Fatal traffic crashes
Traffic safety
Case-crossover design

ABSTRACT

Background: A better understanding of how heat waves affect fatal traffic crashes will be useful to promote awareness of drivers' vulnerability during an extreme heat event.

Objective and Methods: We applied a time-stratified case-crossover design to examine associations between heat waves and fatal traffic crashes during May-September of 2001–2011 in the continental United States (US). Heat waves, defined as the daily mean temperature > 95% threshold for ≥ 2 consecutive days, were derived using gridded 12.5 km^2 air temperatures from Phase 2 of the North American Land Data Assimilation System (NLDAS-2). Dates and locations of fatal traffic crash records were acquired from the National Highway Traffic Safety Administration (NHTSA).

Results: Results show a significant positive association between fatal traffic crashes and heat waves with a 3.4% (95% CI: 0.9, 5.9%) increase in fatal traffic crashes on heat wave days versus non-heat wave days. The association was more positive for 56–65 years old drivers [8.2% (0.3, 16.7%)] and driving on rural roadways [6.1% (2.8, 9.6%)]. Moreover, a positive association was only present when the heat wave days were characterized by no precipitation [10.9% (7.3%, 14.6%)] and medium or high solar radiation [24.6% (19.9%, 29.5%) and 19.9% (15.6%, 24.4%), respectively].

Conclusions: These findings are relevant for developing targeted interventions for these driver groups and driving situations to efficiently reduce the negative effects of heat waves on fatal traffic crashes.

1. Introduction

Temperature plays an important role in the occurrence of traffic crashes (Daanen et al., 2003; Malyshkina et al., 2009; Bergel-Hayat et al., 2013; Basagaña et al., 2015; Liu et al., 2017). The effect of heat waves on fatal traffic crashes is less known compared with other meteorological factors, such as precipitation, snow, wind, fog, and hail. Previous research showed that working in heat waves diminishes human capability to carry out both physical and mental tasks (Ramsey, 1995; Kerslake, 2011), increases accident risk (Ramsey et al., 1983) and leads to heat-related illnesses (e.g., heat exhaustion or stroke), if prolonged (Kilbourne, 1997). Driver performance was reported to deteriorate in hot environments. For instance, drivers become irritable and drowsy (McDonald, 1984) and tend to miss signals (Wyon et al., 1996), drift out of their lane and make large steering adjustments (Mackie and O'hanlon, 1977) in the heat. High temperatures also increase the likelihood of vehicle breakdowns (e.g., flat tires) and make roadways soften or buckle, which may lead to collisions (Vajda et al., 2014).

Many previous studies have demonstrated the negative effects of high temperatures on traffic crashes (Nofal and Saeed, 1997; Brijs et al., 2008; Malyshkina et al., 2009; Basagaña et al., 2011; Bergel-Hayat et al., 2013; Basagaña et al., 2015; Liu et al., 2017). For instance, a relevant study conducted in Indiana, US found that summer weeks with high temperatures were at high-risk in terms of crashes (Malyshkina et al., 2009). An epidemiologic study found that a 1 °C increase in average temperature resulted in a 1%–2% increase in the number of motor vehicle injuries in France and the Netherlands (Bergel-Hayat et al., 2013). A study in Spain used daily data to find that the estimated risk of crashes significantly increased by 2.9% on heat wave days (Basagaña et al., 2015). Liu et al. (2017) found increased odds of motor vehicle collisions associated with extreme heat events during summer months in Maryland, US. For other meteorological factors that might relate to traffic crashes, such as bright sunlight, extreme storms, or haze, few previous studies examined how they affect the association between fatal traffic crashes and the extreme heat event. Moreover, how heat waves may differently affect female or male drivers, drivers at different ages, and with different body mass indices (BMI), as well as driving on different days of the week, time of the day, and on different

* Corresponding author.
E-mail address: yuhaowu@troy.edu (C.Y.H. Wu).

https://doi.org/10.1016/j.aap.2018.07.025
Received 21 April 2018; Received in revised form 8 July 2018; Accepted 18 July 2018
Available online 23 July 2018
0001-4575/

types of roadways with varying speed limits is less studied. One relevant study related to driver age is Liu et al. (2017), who compared three age groups (i.e., 15–19, 20–64, and > = 65 years old) of drivers in motor vehicle collisions involving a single vehicle in different seasons and found the number of collisions in each of these age groups was similar across the four seasons.

Many previous studies focused on how absolute temperatures would lead to traffic crashes (Nofal and Saeed, 1997; Brijs et al., 2008; Malyshkina et al., 2009; Bergel-Hayat et al., 2013). However, acclimation is an important determinant of human activities associated with heat exposure. For instance, people who live in a warmer climate will be able to sustain higher temperatures versus those who live in a colder climate. Therefore, for a nationwide study with diverse climates in the study area, it may be more meaningful to define periods of unusual warmth (i.e., "heat waves") based on deviation from average local conditions rather than absolute temperature thresholds. Heat waves have many different quantitative definitions. When comparing different definitions of heat waves, previous studies have found that relative, mean daily temperature-based heat wave definitions are a simple metric and predictive of mortality and preterm birth (Anderson and Bell, 2009, 2011, Kent et al., 2014). Thus, the present study uses mean daily temperature- > 95th percentile for ≥ 2 consecutive days to define heat wave days (we also present mean daily temperature > 90th, 98th, and 99th percentile for ≥ 2 consecutive days and show their relevant results in Supplemental Materials). Some previous studies focused on heat waves or extreme heat events assigned traffic crashes with the temperature data from the nearest weather stations or the weather stations within a specific area (e.g., Zip code, county, or climatic region) (Basagaña et al., 2011, 2015; Liu et al., 2017). However, the density and spatial distribution of weather stations, as well as the geometric shape and size of the specific areas, might result in exposure measurement error at the locations of traffic crashes. To minimize this error, this study used address-level data (i.e., traffic crashes' locations) and gridded temperature data (with resolution 12.5 km^2) to evaluate whether the traffic crashes occurred in a location experiencing a heat wave.

The objectives of this study are to examine: 1) whether fatal traffic crashes occur at a greater frequency during heat waves at the national level; and 2) whether the associations are different when the analysis is stratified by drivers' gender, age, BMI, as well as day of the week, time of day, speed limit, rural/urban roadways and other meteorological factors (i.e., solar radiation and precipitation).

2. Materials and methods

2.1. Fatal traffic crash records

We obtained the records (N = 261,125) of drivers who were involved in fatal traffic crashes in the continental US for the warm months (May-September) of 2001–2011, from the Fatality Analysis Reporting System (FARS) provided by NHTSA. These fatal traffic crash-related records are non-identifiable, publicly available and only used for research purposes. Each record includes driver demographic information (i.e., gender, age group, height, and weight), the crash date, roadway function class, and the crash location. We selected those records with the valid longitude and latitude information, thus 248,809 records (approximately 95.3% of total records) were considered in subsequent analyses.

2.2. Heat wave indices (HIs)

There is not a universally accepted definition of a heat wave (Smith et al., 2013). This study defined the HI as the daily mean temperature higher than 95% percentile for ≥ 2 consecutive days, because this relatively simple metric has shown to be predictive of mortality and preterm birth in previous studies (Anderson and Bell, 2009, 2011, Kent et al., 2014). We also applied an additional three daily mean temperature-based HIs, using 90%, 98%, and 99% percentile thresholds, in Supplemental Materials – Table S1. Percentile-based HIs (90th, 95th, 98th, and 99th) were determined by ranking all daily temperatures in the warm season (May 1 to September 30) from 2001 to 2011. The temperature data used to calculate HI, and the solar radiation and precipitation data, is 12.5 km gridded data from NLDAS-2 (Cosgrove et al., 2003; Smith et al., 2013). In the present study, this metric was refined to use longitude and latitude information reported on the fatal traffic crash record. The first step was to match the fatal traffic crashes with longitude and latitude information to NLDAS-2 grid cells, and then we determined whether the NLDAS-2 grid cells with the crash dates were on a heat wave day defined by HIs.

2.3. Rurality, weekdays, age, BMI, speed limits, and day/night-times

The analysis was stratified by drivers' demographic factors (i.e., gender, age and BMI), as well as crash-related factors (i.e., rural/urban roadways, weekdays/weekends, speed limits, and day/night time of involved fatal traffic crashes), respectively. In terms of BMI, the data included the weight and height for each fatal crash-involved driver, so that we were able to use BMI (which is used to screen for weight categories that may lead to health problems and calculated by weight in kilograms divided by the square of height in meters). Then, BMI was grouped into three categories: 1) Underweight and normal weight < 24.9 kg/m^2; 2) Overweight – 25.0 to 29.9 kg/m^2; and 3) Obese - ≥ 30 kg/m^2 following CDC's standard weight status categories for adults (Center for Disease Control and Prevention, 2015). For rurality, the traffic crash data from FARS includes the information on the roadway function class, which indicates if the road or highway where the traffic crashes occurred, is considered rural or urban. The roadway function classes at the rural level include: 1) rural-principal arterial-interstate; 2) rural principal arterial-other; 3) rural minor arterial; 4) rural major collector; 5) rural minor collector; 6) rural local road or street; and 7) unknown rural roadway. The urban level had a similar set of seven road types. We mapped the fatal traffic crashes on rural and urban roadways to visualize their spatial pattern (Fig. 1). We grouped the speed limits at the crash locations for three categories: 1) < 30 miles per hour (m/h), which are usually community roads; 2) ≥ 30 and < 55 m/h, which are avenues and boulevards at the town/county/city level; and 3) ≥ 55 m/h, which are highways. For day/night-time, we defined 7 a.m. to 6 p.m. (or 7–18) as the daytime period and other time slots (i.e., before 7 a.m. and after 6 p.m.) as the nighttime period.

2.4. Study design and statistical analysis

Chi-square test was used to examine the difference in drivers' demographic factors (i.e., gender, age and BMI) and other crash-relevant factors (i.e., rural/urban roadways, weekdays/weekends, speed limits, and day/night time of involved fatal traffic crashes) between heat wave days and non-heat wave days. A p-value of ≤ 0.05 is the level of significance set for all statistical tests.

We adopted a time-stratified case-crossover design, which is a statistical method ideally suited to examine short-term exposure with acute outcomes (Basu et al., 2005; Janes et al., 2005a; Crouse et al., 2012). In the case-crossover design, each driver serves as his or her own control; therefore, known and unknown time-invariant confounders, such as BMI, seasonality, and overlap bias, are inherently adjusted by study design (Maclure, 1991). The time-stratified control selection method in this design is frequently used in environmental health studies (Basu et al., 2005; Janes et al., 2005b, a, Crouse et al., 2012; Tong et al., 2012). Moreover, in this time-stratified sampling design, all days that are on the same day of the week and within the same month as the case day are selected as control periods. Similar to a matched case-control design, the case-crossover design uses the case and matched time-stratified control period as the stratum in conditional logistic regression

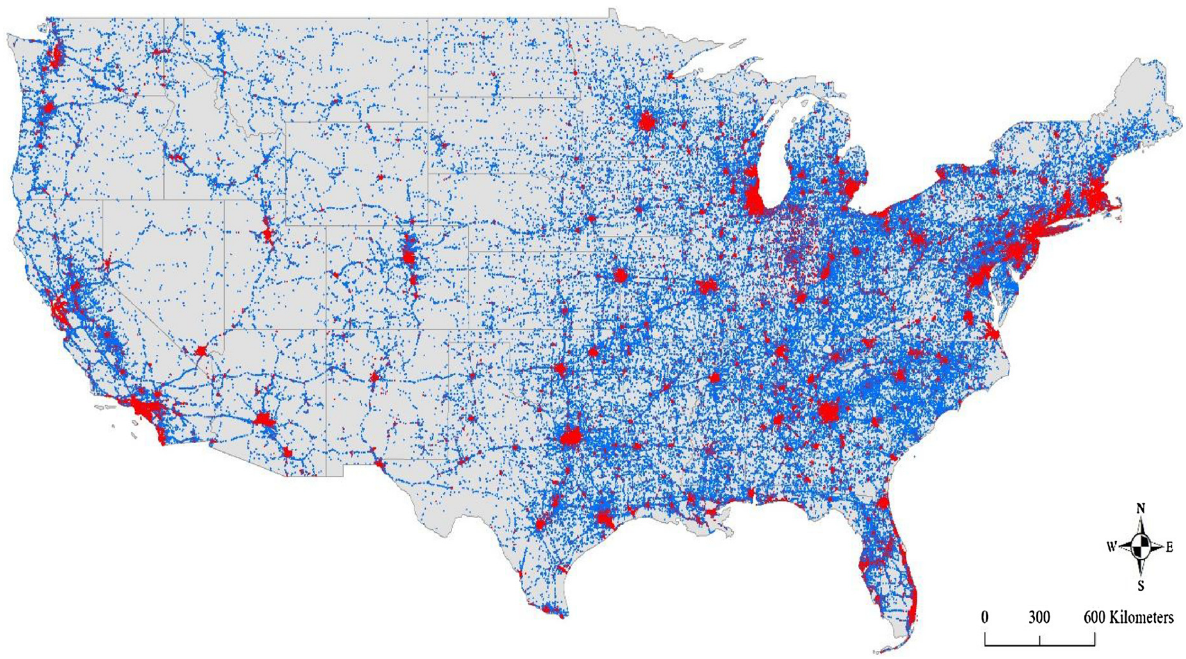

Fig. 1. Fatal traffic crashes occurred on rural (blue points) and urban (red points) roadways in warm months (May-September) of 2001–2011 in continental US. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

models. Analyses were run using IBM SPSS Statistics v20.0 (SPSS Inc., an IBM Company, Chicago, IL, USA). Conditional logistic regression models were used to estimate odds ratios (ORs) and 95% confidence intervals (CIs) for the associations between the outcomes of interest and heat wave days. To summarize statistical results, associations are reported as the percent change in the odds of the outcome on heat wave days compared with non-heat wave days [percent difference = (OR-1) x 100].

3. Results

Table 1 summarizes drivers' demographic factors and other crash-related factors on heat wave days, defined using HI95th (i.e., daily mean temperature > 95th percentile for ≥ 2 consecutive days), versus non-heat wave days. Results of the chi-square test show that drivers involved in fatal traffic crashes on heat wave days had different demographic factors compared with those drivers that had fatal traffic crashes on non-heat wave days. For instance, in fatal traffic crashes that occurred on heat wave days, the number of obese drivers and 46–55 or 56–65 years old drivers was higher than expected. Moreover, the numbers of drivers involved in fatal traffic crashes on rural roadways were significantly higher on heat wave days compared with non-heat wave days. Results also show that the number of fatal traffic crashes were heightened when the heat wave days had high solar radiation or did not have precipitation. We also summarized drivers' demographic factors and other crash-related factors on heat wave days, defined using other HIs with 90th, 98th, and 99th percentile thresholds in Supplemental Materials, Table S2.

Associations are reported in Figs. 1 and 2 as the percentage change in the odds [(OR-1) x 100] of fatal traffic crashes on heat wave days (defined using HI95th) compared with non-heat wave days. Fig. 2 shows that the association between fatal traffic crashes and heat waves was significantly positive for all drivers, with 3.4% (95% CI: 0.9%, 5.9%) higher odds of fatal traffic crashes on heat wave versus non-heat wave days. When the analysis was stratified by gender, fatal traffic crashes with both male and female drivers were positively associated with heat wave days, with 3.0% (95% CI: 0.1%, 5.9%) and 5.0% (95% CI: 0.1%, 10.2%) higher odds on heat wave days respectively. At the same time, fatal traffic crashes with 26–35, 46–55, and 56–65 years old drivers had a significantly positive association, with 6.2% (95% CI: 0.5%, 12.2%), 6.8% (95% CI: 0.6%, 13.3%), and 8.2% (95% CI: 0.3%, 16.7%) higher odds respectively. Regarding BMI, obese drivers (BMI ≥ 30 kg/m^2) had 3.0% (95% CI: 0.0%, 6.0%) higher odds in fatal traffic crashes on heat wave days than non-heat wave days.

Fig. 3 shows the associations between fatal traffic crashes and heat waves stratified by day of the week, time of day, speed limits, and rurality. Results show that the associations were positive for weekdays, with 4.7% (95% CI: 1.8%, 7.8%) higher odds of fatal traffic crashes on heat wave versus non-heat wave days. In terms of time of day, results indicate that daytime (7–18) had significantly positive associations, with 4.3% (95% CI: 0.9, 7.7) higher odds of fatal traffic crashes on heat wave versus non-heat wave days. Meanwhile, heat wave days were significantly positively associated with fatal traffic crashes on the roadways with speed limits ≥ 30 and < 55 m/h (4.8% increase, 95% CI: 0.9%, 8.8%) and ≥ 55 m/h (3.4% increase, 95% CI: 0.0%, 6.9%). For rurality, rural roadways had a significantly positive association (6.1% increase, 95% CI: 2.8%, 9.6%). We also tested three other HIs, defined by the daily mean temperature > 90th, 98th, or 99th percentile for ≥ 2 consecutive days, to examine the association between fatal traffic crashes and heat waves (Supplemental Materials, Figures S1 to S8). They had close results with the current HI using 95th percentile threshold.

Fig. 4 shows the associations between fatal traffic crashes and heat waves stratified by solar radiation and precipitation. Results show that heat wave days were significantly positively associated with fatal traffic crashes in the middle tertile (24.6% increase, 95% CI: 19.9%, 29.5%) and the upper teritile (19.9% increase, 95% CI: 15.6%, 24.4%) of solar radiation, the association became significantly negative when in the lower tertile (-48.4% decrease, 95% CI: -51.4%, -45.2%). For precipitation, the association was significantly positive on non-precipitation days (10.9% increase, 95% CI: 7.3%, 14.6%) and negative on precipitation days (-4.4% decrease, 95% CI: -7.7%, -0.9%).

4. Discussion

We examined the associations between fatal traffic crashes and heat waves. Results show heat wave days, defined using the daily mean

Table 1
Summary of fatal crash involved driver data in the US during 2001–2011.

	Heat wave days[1] [N (%)][2]	Non-heat wave days[3] [N (%)]	p^4
All drivers	10352 (100)	237,094 (100)	
Gender			0.425
Male	7648 (74.8)	174,218 (74.4)	
Female	2578 (25.2)	59,825 (25.6)	
Age			< 0.001
16–25	2584 (25.1)	61,152 (25.9)	
26–35	1993 (19.3)	44,631 (18.9)	
36–45	1768 (17.2)	42,876 (18.2)	
46–55	1704 (16.5)	36,418 (15.4)	
56–65	1075 (10.4)	22,923 (9.7)	
> 65	1179 (11.4)	27,758 (11.8)	
BMI (kg/m^2)			< 0.001
< 24.9 Underweight or normal weight	1178 (11.4)	28,799 (12.2)	
25.0-29.9 Overweight	2072 (20.1)	49,995 (21.1)	
> = 30 Obese	7078 (68.5)	157,710 (66.7)	
Day of the week			< 0.001
Weekdays	7157 (69.1)	156,404 (66.0)	
Weekends	3195 (30.9)	80,690 (34.0)	
Time of day (hour)			0.600
Daytime (7–18)	5694 (55.2)	130,875 (55.5)	
Nighttime (0–6, 19–23)	4616 (44.8)	104,978 (44.5)	
Speed limit (m/h)			0.493
Low speed limit (< 30)	458 (4.5)	10,745 (4.6)	
Medium speed limit (> = 30, < 55)	4224 (41.8)	97,925 (42.3)	
High speed limit (> = 55)	5423 (53.7)	122,914 (53.1)	
Rurality			0.010
Rural roadway	5927 (57.4)	132,682 (56.1)	
Urban roadway	4394 (42.6)	103,677 (43.9)	
Solar radiation (daily mean watts per square meter - W/m^2)			< 0.001
Lower tertile[5]	1347 (13.0)	81,120 (34.2)	
Middle tertile	4283 (41.4)	78,219 (33.0)	
Upper tertile	4722 (45.6)	77,755 (32.8)	
Precipitation (daily total kg/m^2)			< 0.001
0	5650 (54.6)	115,822 (48.9)	
> 0	4702 (45.4)	121,272 (51.1)	

Note: 1: Only drivers involved in fatal traffic crashes on heat wave days, defined using HI95th, are selected; 2. N is the number of drivers involved in fatal traffic crashes on heat wave days using that HI and % is the percentage of drivers in that category among all drivers involved into the fatal traffic crashes; 3. All drivers involved in fatal traffic crashes on heat wave days and non-heat wave days are selected. 4: p-value is the result of the chi-square test to test the difference between the driver group involved in fatal traffic crashes on heat wave days and the driver group involved in fatal traffic crashes on non-heat wave days. 5: Tertiles were determined using the values of solar radiation in all fatal traffic crash cases.

temperature > 95% threshold for ≥2 consecutive days, were associated with 3.9% (95% CI: 0.4%, 7.6%) higher odds of fatal traffic crashes versus non-heat wave days. After stratifying the analysis, the significantly positive association became stronger in female (5.0% increase, 95% CI: 0.1%, 10.2%), 26–35 (6.2% increase, 95 CI: 0.5%, 12.2%), 46–55 (6.8% increase, 95% CI: 0.6%, 13.3%) and 56–65 (8.2% increase, 95% CI: 0.3%, 16.7%) years old drivers, as well as weekdays (4.7%, 95% CI: 1.8%, 7.8%), daytime (4.3%, 95% CI: 0.9%, 7.7%), medium speed limit (4.8%, 95% CI: 0.9%, 8.8%), and rural roadways (6.1% increase, 95% CI: 2.8%, 9.6%). This suggests that these groups and driving in these situations may be more sensitive to heat waves or increase the risk of fatal traffic crashes associated with heat waves.

Previous research examining traffic crashes during heat waves defined the heat wave days as the daily maximum and minimum temperature > 95% threshold for ≥2 consecutive days; they found a significant positive association with the maximum temperature-based HI and a non-significant negative association with the minimum temperature-based HI (Basagaña et al., 2015). We used mean temperature-based HIs in this study following previous studies showing associations with mortality and preterm birth (Anderson and Bell, 2009, 2011, Kent et al., 2014).

The risk of drivers with different BMIs to traffic crashes associated with heat waves is less well studied. Our results show that when the analysis was stratified by drivers' BMI, obese drivers (BMI ≥ 30 kg/m^2) had a significantly positive association between fatal traffic crashes and heat wave days versus non-heat wave days, although other BMI groups have positive but non-significant odds (Fig. 2). The US has a high prevalence of obesity, which was approximately 36.5% among adults in 2011–2014 (Ogden et al., 2015) and previous studies have shown obese drivers face a heightened risk of fatal injury in traffic crashes (Viano et al., 2008; Rice and Zhu, 2014).

Some researchers found that driving performance in a comfortable temperature would be better than in a cold or hot environment (Wyon et al., 1996; Daanen et al., 2003). In the US, vehicle air-conditioning use was estimated to range from 43% to 49% (Farrington and Rugh, 2000). We did not have data to show whether vehicle air-conditioning use was different during our study period (May-September of 2001–2011). Air-conditioning may not cancel out deterioration of driving performance by heat because thermal comfort in a vehicle cabin may be affected by air velocity, environmental radiation, and clothing insulation (Farzaneh and Tootoonchi, 2008). Moreover, the effects of exposure to high temperature outdoors can be indirect and time-lagged, such as dehydration (Grandjean and Grandjean, 2007) and poor sleep quality in summer months (Radun and Radun, 2006).

We also examined the association between heat wave days and fatal traffic crashes stratified by solar radiation and precipitation. Our results show that when the analysis was stratified by precipitation, fatal traffic crashes were increased on non-precipitation heat wave days [10.9% increase odds (95% CI: 7.3%, 14.6%)] and decreased on precipitation days. The negative association found with precipitation is consistent with some previous findings on the negative correlation between precipitation and the number of traffic crashes (Andrey, 2010; Bergel-Hayat et al., 2013; El-Basyouny et al., 2014), although others found a positive correlation (Brijs et al., 2008; Qiu and Nixon, 2008; Jung et al., 2011; El-Basyouny and Kwon, 2012). For solar radiation, our results show that the association was stronger in the middle and upper tertiles of solar radiation than the lower tertile, suggesting heat waves might affect driving performance via solar radiation. This finding echoes previous results showing the positive association between sunshine duration and the number of traffic crashes (Brijs et al., 2008).

This study examined associations across the continental US, which is a national level study area that combines diverse climates and different driving environments. Thus, we used relative heat wave definitions (HIs) instead of absolute temperatures as a proxy for heat exposure in the analysis. In many areas—especially rural areas—the NLDAS-2 12.5 km size gridded data offers a closer spatial match for HI calculation than the nearest weather station data. We also used the latitude and longitude information of fatal traffic crashes to determine which HI grids they are located within. The address-level analysis is able to provide more accurate exposure estimates than ZIP code- or county-level analysis, which might have errors in the results due to the geometric shape and size of ZIP codes and counties. Furthermore, the nationwide data includes 11 years (2001–2011) of fatal traffic crashes officially recorded by NHTSA and daily mean temperature data in summer months from NASA for HI calculation. Therefore, there was substantial power to detect associations between heat waves and the fatal traffic crashes.

Policy and practice implications of the findings of this research include 1) the findings on the positive association between fatal traffic crashes and heat waves can be applied to the national policies and interventions aiming to improve transportation safety during extreme weather events; 2) The findings of this research on the association for different age groups of drivers (particularly the 46–55 and 56–65 age groups with more positive associations) help transportation authorities and policymakers target populations when developing effective heat

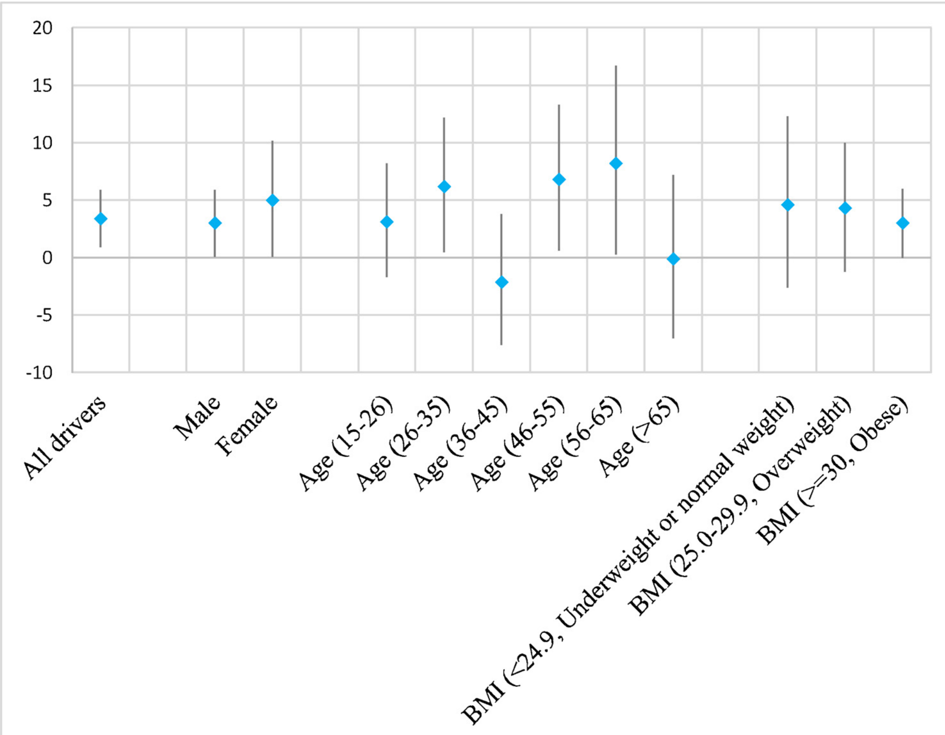

Fig. 2. Percent change (95% CI) in fatal traffic crashes for all drivers and stratified by drivers' gender, age, and BMI on the day of a heat wave compared with corresponding non–heat wave control days, defined by HI95th. Estimates are derived from ORs and 95% CIs estimated using case-crossover conditional logistic regression models.

wave warning systems for drivers; 3) The more positive association found in driving on rural roadways suggests Traffic Incident Management (which is a program of the Federal Highway Administration and part of the larger Emergency Transportation Operations all-hazards program) can reduce the response time and impacts of fatal traffic crashes by having quick emergency responders in nearby areas during heat waves.

This research has its limitations. First, we lacked traffic volume data to control the effects of traffic volume on crash numbers. However, the time-stratified sampling design in our study (which combines year and month) produced consistent estimated associations with those from models adjusted for traffic volume (Brijs et al., 2008). Second, our study focused on fatal traffic crashes reported to the police. The effects of heat waves on all traffic crashes, including non-fatal or not reported to police traffic crashes, are out of the scope of this study.

5. Conclusions

This study found that heat waves may increase the odds [i.e., 3.4% (95% CI: 0.9, 5.9%)] of fatal traffic crashes in the continental US. This

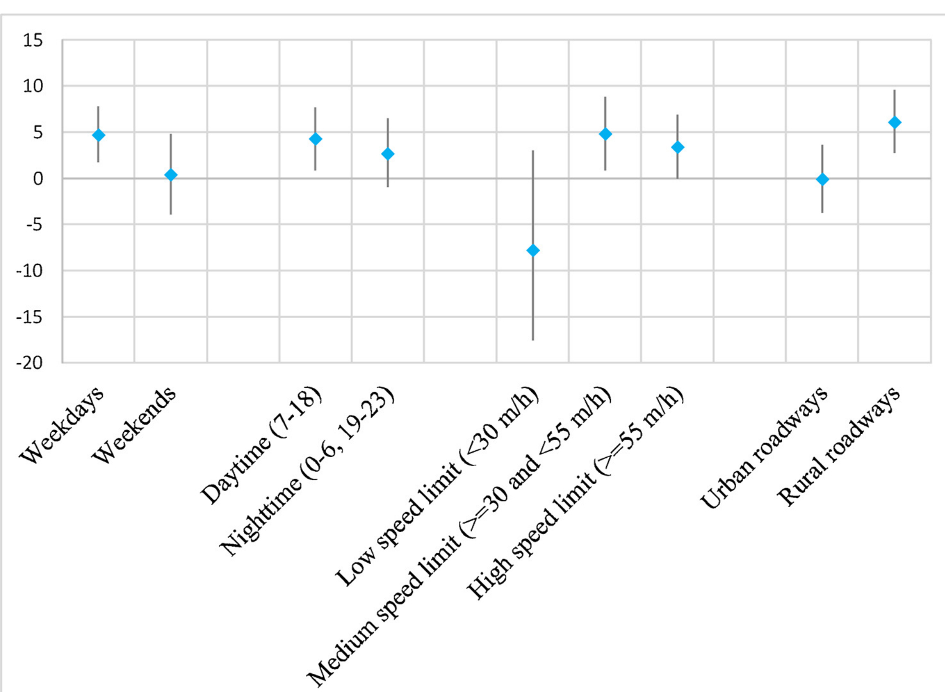

Fig. 3. Percent change (95% CI) in fatal traffic crashes stratified by days of the week, day/night time, speed limits, and urban/rural roadways on the day of a heat wave compared with corresponding non–heat wave control days, defined by HI95th. Estimates are derived from ORs and 95% CIs estimated using case-crossover conditional logistic regression models.

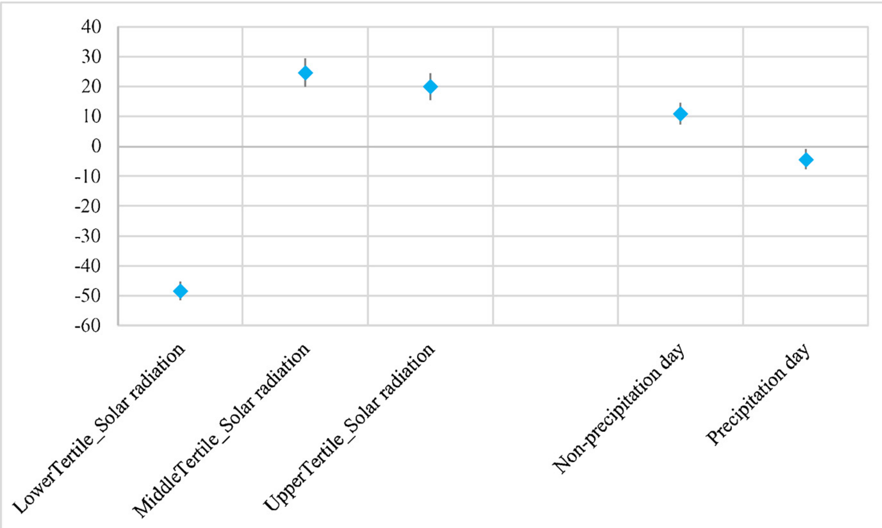

Fig. 4. Percent change (95% CI) in fatal traffic crashes stratified by daily mean solar radiation (W/m^2) and daily total precipitation (kg/m^2) on the day of a heat wave compared with corresponding non–heat wave control days, defined by HI95th. Estimates are derived from ORs and 95% CIs estimated using case-crossover conditional logistic regression models.

finding suggests that previous findings of associations between fatal traffic crashes and high temperatures in regional areas or European countries may also apply in the continental US. Thus, greater emphasis on risk communication regarding the negative effects can help public health officials and transportation authorities to promote awareness and to develop heat wave warning systems for drivers during extreme heat events. Additionally, we found the increased odds in 56–65 years old drivers [8.2% (0.3, 16.7%)] and driving on rural roadways [6.1% (2.8, 9.6%)], suggesting that targeted interventions should focus on these groups and driving situations to efficiently reduce the negative effects of heat waves on fatal traffic crashes. Meanwhile, we found a positive association only when heat wave days were characterized by no precipitation [10.9% (7.3%, 14.6%)] and medium or high solar radiation [24.6% (19.9%, 29.5%) and 19.9% (15.6%, 24.4%), respectively].

Conflicts of interest

None declared.

Source of funding

This work was in part funded through a postdoctoral fellowship to Connor Y.H. Wu from the Virginia-Maryland College of Veterinary Medicine and a grant from the National Institutes of Health (R01 ES023029 - Principal investigator: Julia M. Gohlke).

Conflicts of interest

None declared.

Data availability statements

The fatal traffic crash data can be downloaded from the Fatality Analysis Reporting System (FARS, or https://www-fars.nhtsa.dot.gov//QueryTool/QuerySection/SelectYear.aspx) provided by the National Highway Traffic Safety Administration (NHTSA). The meteorological data is publicly available from the North American Land Data Assimilation System, Phase 2 (NLDAS-2, or https://ldas.gsfc.nasa.gov/nldas/NLDAS2forcing.php) developed by NASA.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.aap.2018.07.025.

References

Anderson, B.G., Bell, M.L., 2009. Weather-related mortality: how heat, cold, and heat waves affect mortality in the united states. Epidemiology (Cambridge, Mass.) 20 (2), 205–213.
Anderson, B.G., Bell, M.L., 2011. Heat waves in the united states: Mortality risk during heat waves and effect modification by heat wave characteristics in 43 u.S. Communities. Environ. Health Perspect. 119 (2), 210–218.
Andrey, J., 2010. Long-term trends in weather-related crash risks. J. Transp. Geogr. 18 (2), 247–258.
Basagaña, X., Sartini, C., Barrera-Gómez, J., Dadvand, P., Cunillera, J., Ostro, B., Sunyer, J., Medina-Ramón, M., 2011. Heat waves and cause-specific mortality at all ages. Epidemiology 22 (6), 765–772.
Basagaña, X., Escalera-Antezana, J.P., Dadvand, P., Llatje, Ò., Barrera-Gómez, J., Cunillera, J., Medina-Ramón, M., Pérez, K., 2015. High ambient temperatures and risk of motor vehicle crashes in catalonia, spain (2000–2011): a time-series analysis. Environ. Health Perspect. 123 (12), 1309.
Basu, R., Dominici, F., Samet, J.M., 2005. Temperature and mortality among the elderly in the united states: a comparison of epidemiologic methods. Epidemiology 16 (1), 58–66.
Bergel-Hayat, R., Debbarh, M., Antoniou, C., Yannis, G., 2013. Explaining the road accident risk: weather effects. Accid. Anal. Prev. 60, 456–465.
Brijs, T., Karlis, D., Wets, G., 2008. Studying the effect of weather conditions on daily crash counts using a discrete time-series model. Accid. Anal. Prev. 40 (3), 1180–1190.
Center for Disease Control and Prevention, 2015. How is bmi Interpreted for Adults? Center for Disease Control and Prevention.
Cosgrove, B.A., Lohmann, D., Mitchell, K.E., Houser, P.R., Wood, E.F., Schaake, J.C., Robock, A., Marshall, C., Sheffield, J., Duan, Q., 2003. Real-time and retrospective forcing in the North American land data assimilation system (nldas) project. J. Geophys. Res. Atmos. 108 (D22).
Crouse, D.L., Peters, P.A., Van Donkelaar, A., Goldberg, M.S., Villeneuve, P.J., Brion, O., Khan, S., Atari, D.O., Jerrett, M., Pope, C.A., Brauer, M., Brook, J.R., Martin, R.V., Stieb, D., Burnett, R.T., 2012. Risk of nonaccidental and cardiovascular mortality in relation to long-term exposure to low concentrations of fine particulate matter: a Canadian national-level cohort study. Environ. Health Perspect. 120 (5), 708–714.
Daanen, Ha.M., Van De Vliert, E., Huang, X., 2003. Driving performance in cold, warm, and thermoneutral environments. Appl. Ergon. 34 (6), 597–602.
El-Basyouny, K., Kwon, D.-W., 2012. Assessing Time and Weather Effects on Collision Frequency by Severity in Edmonton Using Multivariate Safety Performance Functions.
El-Basyouny, K., Barua, S., Islam, M.T., 2014. Investigation of time and weather effects on crash types using full bayesian multivariate poisson lognormal models. Accid. Anal. Prev. 73, 91–99.
Farrington, R., Rugh, J., 2000. Impact of Vehicle Air-conditioning on Fuel Economy, Tailpipe Emissions, and Electric Vehicle Range. Preprint. National Renewable Energy Lab., Golden, CO (US).
Farzaneh, Y., Tootoonchi, A.A., 2008. Controlling automobile thermal comfort using optimized fuzzy controller. Appl. Therm. Eng. 28 (14), 1906–1917.
Grandjean, A.C., Grandjean, N.R., 2007. Dehydration and cognitive performance. J. Am. Coll. Nutr. 26 (sup5), 549S–554S.
Janes, H., Sheppard, L., Lumley, T., 2005a. Case–crossover analyses of air pollution exposure data: referent selection strategies and their implications for bias. Epidemiology 16 (6), 717–726.
Janes, H., Sheppard, L., Lumley, T., 2005b. Overlap bias in the case-crossover design, with application to air pollution exposures. Stat. Med. 24 (2), 285–300.

Jung, S., Qin, X., Noyce, D., 2011. Modeling highway safety and simulation in rainy weather. Transp. Res. Record J. Transp. Res. Board 2237, 134–143.

Kent, S.T., Mcclure, L.A., Zaitchik, B.F., Smith, T.T., Gohlke, J.M., 2014. Heat waves and health outcomes in Alabama (USA): the importance of heat wave definition. Environ. Health Perspect. (Online) 122 (2), 151.

Kerslake, D.M., 2011. The Stress of Hot Environments. Cambridge University Press.

Kilbourne, E.M., 1997. Heat waves and hot environments. The Public Health Consequences of Disasters. pp. 245–269.

Liu, A., Soneja, S.I., Jiang, C., Huang, C., Kerns, T., Beck, K., Mitchell, C., Sapkota, A., 2017. Frequency of extreme weather events and increased risk of motor vehicle collision in maryland. Sci. Total Environ. 580, 550–555.

Mackie, R.R., O'hanlon, J.F., 1977. A study of the combined effects of extended driving and heat stress on driver arousal and performance. In: Mackie, R.R. (Ed.), Vigilance: Theory, Operational Performance, and Physiological Correlates. Springer US, Boston, MA, pp. 537–558.

Maclure, M., 1991. The case-crossover design: a method for studying transient effects on the risk of acute events. Am. J. Epidemiol. 133 (2), 144–153.

Malyshkina, N.V., Mannering, F.L., Tarko, A.P., 2009. Markov switching negative binomial models: an application to vehicle accident frequencies. Accid. Anal. Prev. 41 (2), 217–226.

Mcdonald, N., 1984. Fatigue, Safety, and the Truck Driver Taylor & Francis, London, United Kingdom.

Nofal, F.H., Saeed, Aa.W., 1997. Seasonal variation and weather effects on road traffic accidents in riyadh city. Public Health 111 (1), 51–55.

Ogden, C.L., Carroll, M.D., Fryar, C.D., Flegal, K.M., 2015. Prevalence of Obesity Among Adults and Youth: United States, 2011–2014. Centers for Disease Control and Prevention, Hyattsville, MD.

Qiu, L., Nixon, W., 2008. Effects of adverse weather on traffic crashes: systematic review and meta-analysis. Transp. Res. Record J. Transp. Res. Board 2055, 139–146.

Radun, I., Radun, J.E., 2006. Seasonal variation of falling asleep while driving: an examination of fatal road accidents. Chronobiol. Int. 23 (5), 1053–1064.

Ramsey, J.D., 1995. Task performance in heat: a review. Ergonomics 38 (1), 154–165.

Ramsey, J.D., Burford, C.L., Beshir, M.Y., Jensen, R.C., 1983. Effects of workplace thermal conditions on safe work behavior. J. Safety Res. 14 (3), 105–114.

Rice, T.M., Zhu, M., 2014. Driver obesity and the risk of fatal injury during traffic collisions. Emerg. Med. J. 31 (1), 9–12. https://doi.org/10.1136/emermed-2012-201859.

Smith, T.T., Zaitchik, B.F., Gohlke, J.M., 2013. Heat waves in the United States: definitions, patterns and trends. Clim. Change 118 (3), 811–825.

Tong, S., Wang, X.Y., Guo, Y., 2012. Assessing the short-term effects of heatwaves on mortality and morbidity in Brisbane, Australia: comparison of case-crossover and time series analyses. PLoS One 7 (5), e37500.

Vajda, A., Tuomenvirta, H., Juga, I., Nurmi, P., Jokinen, P., Rauhala, J., 2014. Severe weather affecting european transport systems: the identification, classification and frequencies of events. Nat. Hazards 72 (1), 169–188.

Viano, D.C., Parenteau, C.S., Edwards, M.L., 2008. Crash injury risks for obese occupants using a matched-pair analysis. Traffic Inj. Prev. 9 (1), 59–64.

Wyon, D.P., Wyon, I., Norin, F., 1996. Effects of moderate heat stress on driver vigilance in a moving vehicle. Ergonomics 39 (1), 61–75.